A Highly Tunable Sub-Wavelength Chiral Structure for Circular Polarizer

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CONTENTS

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- Proposed chiral structure
  - Origin of chirality
  - Tunability in polarization control
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INTRODUCTION

- Chiral medium
  - composed of particles that cannot be superimposed on their mirror images

- Examples
EM PROPERTY OF CHIRAL MEDIA

- **BI-isotropic** and **BI-anisotropic** media
  - Cross coupling between the electric and magnetic fields along the same direction

Constitutive relations

\[
\mathbf{D} = \varepsilon \cdot \mathbf{E} + \xi \cdot \mathbf{H} \\
\mathbf{B} = \zeta \cdot \mathbf{E} + \mu \cdot \mathbf{H}
\]

- **Aligned** electric dipoles and magnetic dipoles appear *simultaneously* under the action of *an electric field or a magnetic field alone.*
EM WAVE SOLUTION IN CHIRAL MEDIA

- Assume isotropic, lossless and reciprocal chiral media

Constitutive relations

\[
\begin{pmatrix}
D \\
B
\end{pmatrix} = \begin{pmatrix}
\varepsilon_0 \varepsilon_r & -i\kappa/c \\
i\kappa/c & \mu_0 \mu_r
\end{pmatrix}
\begin{pmatrix}
E \\
H
\end{pmatrix}
\]

\(\kappa\), chirality that measures cross-coupling effect between electric and magnetic fields

- Two eigenvalues

\[k_{\pm} = k_0 (n \pm \kappa) \quad n = \sqrt{\varepsilon \mu}\), refraction index of the medium without chirality

- Two eigenvectors

\[E_{\pm} = \frac{1}{2} E_0 (\hat{x} \mp i\hat{y})\]

+, right circularly polarized wave; -, left circularly polarized wave
PROPERTIES OF CHIRAL MEDIA

- Negative refraction
  - Negative refraction index for one circularly polarized wave when both $\varepsilon$ and $\mu$ are positive.
  
  \[ k_{\pm} = k_0 (n \pm \kappa) \quad n = \sqrt{\varepsilon \mu} \]

- Optical activity
  - Rotation of the plane of polarization of linearly polarized wave

- Circular dichroism
  - Different absorption of the left and right circularly polarized wave
REVIEW OF CURRENT WORK

- Existing prototypes
  - 3D chiral structure[1]
  - Planar chiral structure[2]

- Proposed chiral structure
  - Simple 3D chiral geometry
  - Conveniently fabricated on PCB
  - Great capability to manipulate the polarization state of EM waves
  - Large tunability

ORIGIN OF CHIRALITY

- Fundamental mode of the proposed chiral structure
- Two pairs of aligned ME dipoles

(a) 3D of the chiral particle resonating at the fundamental mode

(b) Current distribution viewed from the \( x \) axis and induced ME dipole pair along the \( x \) direction

(b) Current distribution viewed from the \( y \) axis and induced ME dipole pair along the \( y \) direction
TRANSMISSION MATRIX

- Assume a plane wave propagates along the z direction

\[
E_i(r, t) = \begin{pmatrix} i_x \\ i_y \end{pmatrix} e^{i(kz-\omega t)}, \quad E_t(r, t) = \begin{pmatrix} t_x \\ t_y \end{pmatrix} e^{i(kz-\omega t)}
\]

\(i_{x,y}\) and \(t_{x,y}\) are polarization states of incident and transmitted waves.

- Chiral particle modelling

Transmission matrix

\[
\begin{pmatrix} t_x \\ t_y \end{pmatrix} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \begin{pmatrix} i_x \\ i_y \end{pmatrix} = T_{\text{lin}} \begin{pmatrix} i_x \\ i_y \end{pmatrix}
\]

Linear basis

\[
T_{\text{circ}} = \begin{pmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{pmatrix} = \frac{1}{2} \left( \begin{pmatrix} T_{xx} + T_{yy} \\ T_{xx} - T_{yy} \end{pmatrix} + i \begin{pmatrix} T_{xy} - T_{yx} \\ T_{xy} + T_{yx} \end{pmatrix} \right)
\]

Circular basis
TUNABILITY

- Chiral particle with different angle $\alpha$
  - $\alpha$ greatly influences the direction and strength of the induced E and M dipoles, so as the chirality

- Special relationship for $\pm \alpha$

Optical activity: azimuthal rotation angle  
Circular dichroism: ellipticity

\[
\theta = \frac{1}{2} [\arg(T_{++}) - \arg(T_{--})] \\
\eta = \frac{1}{2} \sin^{-1} \left( \frac{|T_{++}|^2 - |T_{--}|^2}{|T_{++}|^2 + |T_{--}|^2} \right)
\]

\[
\theta^\alpha = -\theta^{-\alpha} \\
\eta^\alpha = -\eta^{-\alpha}
\]
TUNABILITY (CONT.)

- Influence of $\alpha$ on the polarization control of wave
  - Since the coupling between the ME dipoles is weaken as $\alpha$ increases, $\theta$ and $\eta$ becomes smaller for larger $\alpha$

\[ \theta^\alpha = -\theta^{-\alpha} \text{ and } \eta^\alpha = -\eta^{-\alpha} \]
CHIRAL CIRCULAR POLARIZER

- Convert an $x$ polarized wave to a circularly polarized wave
  - $|T_{xx}| = |T_{yx}|$, $\arg(T_{xx}) - \arg(T_{yx}) = \pm 90^\circ$

Dielectric substrate: AD600, $\varepsilon_r = 6.15$, $h = 1.524$ mm
Geometric parameters: $a = 2.9$ mm, $b = 2.5$ mm, $w = 0.4$ mm, $p_x = 7$ mm, $p_y = 6$ mm

$180^\circ$ phase difference between the cross-polarized component by switching the orientations of the two arms
CHIRAL CIRCULAR POLARIZER (CONT.)

- Experiment setup

- 54 × 63 unit cells
- 378 × 378 mm²

Two horn antennas:
- linear polarized
- working frequency: 6.57 GHz ~ 9.99 GHz

Measure

Transmission matrix in linear basis

Calculate

\[ T_{\text{circ}}, \theta, \eta \]
CHIRAL CIRCULAR POLARIZER (CONT.)

- Simulation and experiment results
  - Working frequency 9.2 GHz
  - Efficiency 64%
  - Compact size: unit cell size of $0.21 \lambda_0 \times 0.18 \lambda_0$
  - Conveniently implementation of both right- and left-handed circular polarizer
CONCLUSIONS

- Chiral media: symmetry breaking
- Proposed chiral structure
  - No symmetry can be found along x, y and z directions, indicating a strong chirality.
  - There are two ME dipole, and the strengths of the E (M) dipoles can be tuned by changing the angle $\alpha$. Therefore, its polarization control ability can be tuned. Simulation results of the azimuthal rotation angle and ellipticity of the structures with different $\alpha$ have been shown.
  - Both simulated and experiment results have been shown for a right-handed circular polarizer. A left-handed circular polarizer can be easily implemented by reversing the arms.

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